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each step in the procedure has to have access to previous stages and the material context of physical forces the knot is made to resist. The kernel of their reasoning is the claim that the knotting procedure involves higher-level units (“phrases”), which are deployed according to the material context. This is obvious when one thinks of the sophisticated ways of sailor knots. In general, though, the two hands have to mutually coordinate along the procedure, rather than doing one thing after another. Context sensitivity is linked to operational memory requirements, to keep track of each operation, taking the previous and next ones into account at the same time. From this, Camps and Uriagereka claim that the archeological evidence of knots – even if indirect and inferential – provides the best indication available of a cognitive complexity equivalent to that required by human language.

We think that their case can be strengthened in two directions: First, whereas in projectiles and perforated ornaments a single knot may be required to fix two elements together or to string them around the body, in textiles, nets, and basketry a series of knots is involved, within a general constructive plan (therefore, a more complex, context-sensitive, generative procedure). Second, such a series of knots is in the service of recursive patterns, which can be transformed, following distinct axes of symmetry, for example. Simple iterative processes are clearly not enough to generate such complex structures, where each single operation is conditional on the state of the rest of the fabric and the physical forces the knot is supposed to resist.

Besides, knotting cannot be accounted for in terms of Greenfield’s “action grammar,” which is equivalent to a finite-state automata. She contented that the structural complexity of language can be also found in hierarchical organization of action. The kinds of actions she paid attention to, though, such as “Russian dolls” inclusion, are developmentally easier than knot tying is, and they are also within the reach of non-human primates (whereas knots are beyond the capacities of chimpanzees, according to Josep Call, personal communication). Therefore, the attempt to view recursion in terms of Greenfield’s “action grammar,” as it has been recently suggested (Fujita 2009), does not pay proper attention to the context sensitivity of recursion.

On the other hand, the proposed connection between knotting and language entails that the program proposed by Hauser et al. (2002) got it right that recursion is uniquely human, but wrong that it is a uniquely linguistic capacity, even if the evidence is still not enough to decide how it came about: It could be a general capacity, deployed in different domains, or a domain-specific one that was exapted in others (Barceló-Coblijn, in press). It also offers a plausible hypothesis to set apart the linguistic capacities of *sapiens* and *neanderthal*, given that both species cannot be distinguished at the speech level (Barceló-Coblijn 2011). In summary, context-sensitive rules offer a principled mark of modern humanity, beyond the typical lists of modern behaviors that can be found in archeology (Henshilwood & Marean 2003).

## Tool innovation may be a critical limiting step for the establishment of a rich tool-using culture: A perspective from child development

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**Abstract:** Recent data show that human children (up to 8 years old) perform poorly when required to innovate tools. Our tool-rich culture may be more reliant on social learning and more limited by domain-general constraints such as ill-structured problem solving than otherwise thought.

Vaesen is right to identify the tension between the need for reliable conservation of tool forms and the need for deviation from reliable reproduction if new tools are to be created. Yet, he does not draw a clear enough distinction between the cognitive demands of tool *innovation* and other aspects of tool use. Tool innovation is seen when individuals make a tool to solve a problem without learning socially or having seen a model solution. Where Vaesen refers to human children’s tool use, it is to emphasise human beings’ strengths from a very early age (e.g., sect. 4). However, taking a developmental perspective on human tool use has shown that tool innovation may be particularly difficult for human children, compared with using pre-made tools. Successful innovation in older children and adults is needed to explain the unique richness of human tool culture, whereas the difficulty of innovation observed in human children casts new light on the importance of other abilities, such as social learning, for retaining hard-won innovations.

We (Beck et al. 2011) tested human children on a tool making task based on Weir et al.’s (2002) wire bending problem. This task was originally made famous by the successes of a New Caledonian crow (*Corvus moneduloides*) and more recently rooks (*Corvus frugilegus*) (Bird & Emery 2009). Having previously used a hook to retrieve a bucket from a tall vertical tube, these corvids were then able to fashion a straight piece of wire into a hook to solve the task: that is, they used novel means to make a familiar tool. We questioned whether children would innovate a novel tool, critically without having seen the solution to the task (a hook).

Children up to 5 years old found it near impossible to innovate a novel tool to solve this task, and it was not until 8 years of age that the majority of children succeeded (Beck et al. 2011). Children’s difficulty was replicated on a task requiring them to unbend a bent wire to make a long, straight tool (Cutting et al. 2011) and on tool-innovation tasks involving other materials and other transformations (i.e., adding and subtracting from the tool object as well as bending; Cutting et al., under review). The results could not be attributed to a lack of causal understanding: Young children readily used a pre-made hook tool to solve the vertical tube task (Beck et al. 2011, Experiment 1). Nor could results be explained by a pragmatic resistance to adapting the materials: Children’s difficulties remained in the face of ample encouragement to reshape the wire (a pipe cleaner). We gave children pre-trial experience manipulating the materials, encouraged them to “make something,” and demonstrated tool manufacture on a different task (see Cutting et al. 2011).

Children’s ability to select an appropriate pre-made tool indicates that they did not lack the causal knowledge to solve the task (in Vaesen’s terms, *analogical causal reasoning*; see sect. 4). Furthermore, when an adult demonstrated how to make an appropriate tool, almost all children (97%) found it apparently trivially easy to *manufacture* their own tool and fish the bucket from the tube (Beck et al. 2011). Why, then, is tool *innovation* so late developing?

One possibility is that an over-reliance on social learning and/or teaching (see sects. 7 and 8) prevents children from innovating for themselves. We agree with Vaesen that human children are experts at learning from others. But a species that evolves to pass on information so efficiently to new learners does so at a cost. It is inefficient and possibly counterproductive for children to try to generate their own solutions to problems as well as adopt them from others. At least in childhood, if not also in adult life, the ability to innovate may be sidelined in preference to learning from the more experienced individuals who share our goals and are motivated to collaborate with us (see sect. 9).

However, we doubt that this will be the full explanation. Vaesen argues that developing an advanced technological

culture requires trial-and-error learning and causal understanding. In addition, we suggest that tool innovation is challenging because it makes distinctive demands on executive function. In cognitive and neuropsychological investigation of executive function, “ill-structured” problems are tasks that do not exhaustively define the means of getting from the start point to the goal, but instead require participants to generate such structure for themselves (Goel 1995). From this perspective, tool innovation is clearly an intrinsically “ill-structured” problem: Participants know the goal (e.g., of retrieving the bucket from the tube), and their start point includes the necessary materials (e.g., the wire), but they must generate for themselves the strategy of using the materials to make the necessary tool. As ill-structured problem solving has been associated with late-maturing areas of medial prefrontal cortex (Dumontheil et al. 2008), it is likely to be limited in young children. Hence, unlike trial-and-error learning and causal understanding, which may be observed in young children, difficulty with ill-structured problem solving may explain why children find tool innovation so surprisingly difficult.

Recognising that tool innovation might be an intrinsically difficult problem helps us understand why the capacity for social learning is so important for the development and maintenance of a tool-using culture in both humans and non-human animals: Social learning avoids individuals having to “reinvent the wheel” for themselves. Furthermore, if tool innovation requires ill-structured problem solving, this might help explain why tool cultures of non-human animals are less rich than those of humans. Importantly, though, this leaves open the question of how non-human animals develop the tools that they have. One possibility is that they rely only on trial and error, the useful products of which are maintained through social learning. Another possibility is that tool cognition provides a window onto non-human animals’ ill-structured problem solving, through which we might gain important understanding about the origins of executive control.

## Tool use as situated cognition

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**Abstract:** Vaesen disregards a plausible alternative to his position, and so fails to offer a compelling argument for unique cognitive mechanisms. We suggest an ecological alternative, according to which divergent relationships between organism and environment, not exotic neuroanatomy, are responsible for unique cognitive capacities. This approach is pertinent to claims about primate cognition; and on this basis, we argue that Vaesen’s inference from unique skills to unique mechanisms is unwarranted.

Humans are often observed using multipurpose smartphones to listen to podcasts, surf the Web, and plan international travel. By contrast, even the most sophisticated non-human primates only use single-purpose tools for situation-specific purposes. Whereas wild chimpanzees, for example, use reeds to fish for termites, they never build tools with multiple components and they never use tools in ways that diverge from the situation-specific purpose for which they were created. Put simply, there are undeniable, significant, and manifest differences in the tool-using *behavior* of human and non-human primates. Vaesen maintains that such differences are best explained by reference to evolutionarily discontinuous cognitive mechanisms. He argues that our

comparative advantage in eight cognitive capacities suffices to establish “a major cognitive discontinuity between us and our closest relatives” (sect. 1). We disagree.

The term *capacity* has a variety of distinct meanings in the cognitive and biological sciences: It can denote a trait, ability, or mechanism; and although evolutionary pressures sometimes call for the evolution of novel mechanisms, it is generally less expensive to integrate, redeploy, or recalibrate existing mechanisms than it is to build new ones from scratch (Gould & Vrba 1982; Shubin & Marshall 2000; Simon 1996). On the related assumption, that permutations “of the old within complex systems can do wonders” (Gould 1977), even an evolutionary gradualist can acknowledge unique skills while rejecting appeals to new mechanisms. To establish more than the banality that there are uniquely human traits and abilities, Vaesen must demonstrate that these traits and abilities depend on phylogenetically novel wetware. But we hold that his argument is inconclusive, because it ignores a salient explanatory alternative: namely, the hypothesis that cognitively sophisticated tool use depends not on phylogenetically novel wetware, but on the appropriation of social and environmental scaffolding. We invite Vaesen to consider this explanation, for it is simpler than the appeal to unique mechanisms, and therefore preferable even by his own standards.

To make the case for this, we must note that non-human primates use tools in ways suggestive of several (at least) *proto-human* cognitive capacities. Wild chimpanzees and capuchins use tools to obtain food that is out of reach, crack nuts with “hammers,” and sponge liquid with leaves (Boesch & Boesch-Achermann 2000; Frigaszy et al. 2004; Whiten et al. 1999); and although neither vervets nor cotton-top tamarins use tools in the wild, both can be trained to do so in the laboratory (Santos et al. 2003). Of course, many non-human primates fail to represent the functional properties of their tools (cf. Povinelli 2000). But wild chimpanzees use different tools at different kinds of termite nests, show selective preferences for different materials, and repeatedly visit nests with reusable tools (Sanz & Morgan 2010) and recent data suggest that they use multi-functional tools (Boesch et al. 2009). Furthermore, captive capuchins can discriminate between functionally appropriate and inappropriate throwing tools (Evans & Westergaard 2006); and looking-time methods reveal that cotton-top tamarins and rhesus macaques perceive changes in functional properties as relevant to tool use, but color change as irrelevant (Santos et al. 2003; for vervets and lemurs, see Hauser & Santos 2007). Finally, repeated experience with tools appears to lead to a more sophisticated understanding of their functionally relevant features (Santos et al. 2003, p. 280).

Next, we contend that an ecologically valid approach to cognition requires attending to both the environment in which traits are expressed and the complex *relationships* between organisms and their embedding environment. Although it is sometimes legitimate and productive to focus on internal mechanisms, cognitive processes (including categorization, inference, and reasoning) are often better understood by reference to coupled organism-environment systems (Hutchins 2008). Consider two uncontroversial examples: When chimpanzees are trained to exploit abstract, symbolic resources, they show a pronounced increase in executive control and inhibition (Boysen & Berntson 1995). Similarly, when human beings supplement their internal capacities for working memory and mathematics with external resources such as pens and paper, we are capable of executing a significantly wider range of computations than we otherwise could (Carruthers 2002; Rumelhart et al. 1986). As an organism’s capacities are delineated by the tasks it is able to perform, we contend that many capacities are likely to depend on environmental scaffolding (Barrett 2011; Clark 2008).

We suggest that Vaesen should consider the merits of a more ecological approach to uniquely human traits. Relatively minor modifications of primate neuroanatomy (underwritten by the increase in volume of the prefrontal cortex and intimately